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MEASURED BLOCKAGE EFFECTS ON BLUFF BODIES IN CLOSED AND OPEN WI--ETC(U)
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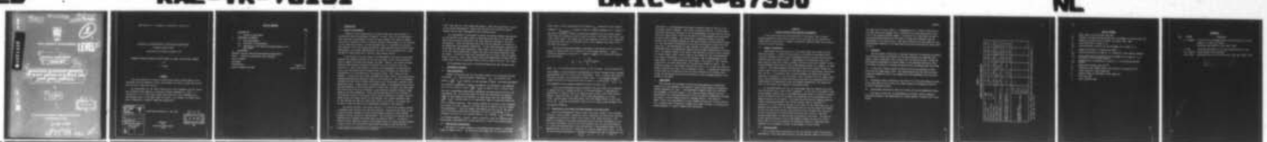

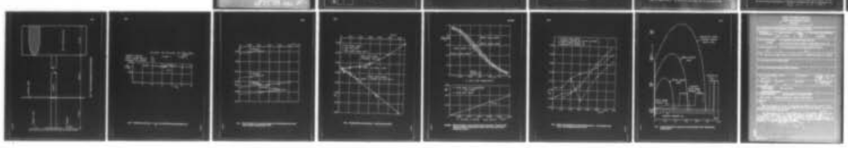

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MEASURED BLOCKAGE EFFECTS ON BLUFF BODIES IN CLOSED AND OPEN WIND TUNNELS

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SUMMARY

The base pressure of a series of square flat plates, placed normal to the airstream, has been measured in three wind tunnels, two with a closed test section and one with an open test section.

The measurements in the closed tunnels are in fair agreement with the theory due to Maskell which predicts a correction linearly dependent on C_DS/C. A correction of $-0.2 \times$ (the closed tunnel correction) is a fair approximation to the blockage effect in the open tunnel for $C_DS/C < 0.03$ though, for larger blockage, a dependence on $(C_DS/C)^2$ seems more appropriate.

Departmental Reference: Aero 3446

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1 INTRODUCTION

1.1 Method of measurement

A theory of the blockage effects on bluff bodies and stalled wings in a closed wind tunnel was published by Maskell[1] in 1963. Part of the confirmatory data consisted of measurements of drag and base pressure on a series of square flat plates, varying in size but otherwise similar, placed normal to the airstream in two closed wind tunnels. No wake-blockage theory is available for open-jet wind tunnels, but it was thought worthwhile to make similar drag and base-pressure measurements to determine experimentally the order of the blockage effect, using the RAE 5ft tunnel which has a circular, open working section.

It was found at an early stage of the measurements that both drag and base-pressure were markedly affected by the size and shape of the sting and balance used to support the plates and measure the drag*. However, the relation between drag and base-pressure postulated by Maskell[1] was still found to hold (see section 2.1), and it was decided to proceed with measurements of base-pressure only, since the plates could be mounted with less interference if there was no drag balance to be incorporated in the support system. Fig 1 shows the rig adopted. A rigid strut was fitted, spanning the tunnel, with a 1.04m long spindle extending upstream and carrying a plate at its forward end. Three 0.7mm diameter bracing wires were used to locate the forward end of the spindle, attached 76 mm behind the plate. A small effect of Reynolds number on the measured base pressure had been observed in the previous series of tests[1] and, as before, the wind speed was varied with plate size to maintain an approximately constant Reynolds number based on the plate dimensions. Three pressure-tapping points were available in the back face of most of the plates, but no radial variation of pressure could be found, within the normal scatter of the readings, and a simple arithmetic mean of the readings was taken for plates with three or two holes. For plates with one hole, a mean was taken of two independent readings of this pressure.

Six plates varying in area from 0.0032 m^2 to 0.1130 m^2 and spindles varying in diameter from 6.35 mm to 36.3 mm were available. Each plate was tested on two or more different spindles so that a base pressure corrected to zero spindle-diameter could be obtained by extrapolation. Full details of the plates, and the combinations of spindles and speeds used, are given in Table 1. In order to obtain a direct comparison between the blockage effects in closed and open tunnels, a similar series of base-pressure measurements was made in both the RAE No.1

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* These effects are discussed in the Appendix.

$11\frac{1}{2}$ft × $8\frac{1}{2}$ft and 4ft × 3ft closed wind tunnels. These were essentially a repeat of the earlier measurements[1], except that the effect of varying the spindle diameter had not been investigated in the original series.

As a preliminary to each series of tests, the static pressure was measured at the position in the empty tunnel at which the plates were to be installed. Then, with each plate in position, the total head just upstream of the plate was measured. These two quantities were then used as references to define the non-dimensional base-pressure coefficient. It was found necessary to measure the total head for each plate separately, rather than to use the empty-tunnel value, in the 5ft tunnel particularly, because the wake of the plates persisted round the tunnel. In the 5ft tunnel this discrepancy rose to 0.012q with the largest plate, in the No.1 $11\frac{1}{2}$ft × $8\frac{1}{2}$ft tunnel it was just detectable at 0.001q with the largest plate, while no measurable effect could be found in the 4ft × 3ft tunnel.

The measurements were made at intervals between June 1965 and March 1966.

2 DISCUSSION OF RESULTS

2.1 Drag measurements

Maskell[1] postulates that for flat plates normal to the airstream the drag coefficient, C_D , and base-pressure coefficient, C_{p_b} , are related by the formula, $C_D/\left(1 - C_{p_b}\right)$ = constant, as the blockage is varied. The drag measurements were subject to appreciable support interference, as discussed in the Appendix, but it is of interest to plot $C_D/\left(1 - C_{p_b}\right)$, as shown in Fig 2, using in each case the corresponding base-pressure coefficient obtained with the plate on the drag-balance rig. If the four points for which the interference was greatest (shown by solid symbols) are excluded, it would appear that the relationship, $C_D/\left(1 - C_{p_b}\right)$ = constant, holds for an appreciable range of sting interference as well as blockage variation. The constant, deduced as the mean of the 14 measurements shown, is 0.836, compared with 0.837 deduced by Maskell from the original five measurements. Since the support interference was kept low for the final series of pressure measurements, discussed in section 2.2 following, it is considered justified to use a derived value of $C_D = 0.836\left(1 - C_{p_b}\right)$ in forming the blockage parameter, $C_D(S/C)$, which is used as a basis for comparing the base-pressure measurements (S = plate area and C = tunnel cross-section area).

2.2 Base-pressure measurements

The effect of spindle diameter on the measured base pressure in the open tunnel is shown in Fig 3. The effect is fairly small and, as indicated by the 151

drawn lines, is well represented by the formula, C_{p_b} (corrected to zero spindle diameter) = $C_{p_b \text{ measured}} - 0.04(d/\ell)$, where d = spindle diameter and ℓ = length of one side of the plate. Similar results were obtained in the two closed tunnels except that the constant was about -0.065 in the 4ft × 3ft tunnel and -0.03 in the $11\frac{1}{2}$ft × $8\frac{1}{2}$ft tunnel. The larger value of the constant in the 4ft × 3ft tunnel may be associated with the low turbulence level, 0.01%, compared with about 0.5% in the other two tunnels.

The base-pressure measurements, corrected to zero spindle size as described above, are shown in Fig 4 as a function of the blockage parameter, $C_D S/C$, derived as described in section 2.1. Maskell[1] suggests, for closed wind-tunnels, the relationship:

$$C_{p_b} = C_{p_c} + \frac{1 - C_{p_c}}{C_{p_c}} (C_D S/C) ,$$

where C_{p_c} is the base-pressure corrected to zero blockage. A line, deduced from this formula, is drawn through the measurements at higher blockage values, showing good agreement with this form of the relationship. There is however some departure from this straight line relationship at small values of the blockage parameter, though this does not represent more than 1% error in estimating $\left(1 - C_{p_c}\right)$ or C_{p_c}. This compares with an apparent measuring accuracy of about 0.5%.

If all the base-pressure values obtained in the open tunnel are considered, it appears that the blockage correction to the base-pressure is approximately proportional to $(C_D S/C)^2$, and is of opposite sign to that in the closed tunnels. However, within the limit of $C_D S/C < 0.03$ a fair approximation is to take -0.02 × (closed tunnel correction) which, over this range, differs by less than 0.5% of $\left(1 - C_{p_b}\right)$ from the parabolic curve, and is in equally good agreement with the measured pressures.

2.3 Distortion of the tunnel airstream boundary in an open tunnel

Mean flow measurements[2] behind a square flat plate normal to the airstream indicate a closed 'bubble' behind the plate, containing circulatory flow, and with a maximum cross-section of about 3.2S at about $1.5\sqrt{S}$ behind the plate. The effect of blockage on the tunnel airstream cross-section was investigated in the 5ft tunnel by making a series of pitot measurements near the airstream boundary, in a plane 250 mm downstream of the plate position - corresponding roughly to the
151 maximum bubble cross-section - using the 127, 180 and 220mm square plates. As for the base-pressure measurements, a different wind-speed was used for each plate size

(see Table 1), and measurements were made on opposite sides of the jet in the horizontal plane of symmetry. The results are shown in Fig 5a. For each plate the points plotted are the mean of the two measurements on either side of the jet, while the 'empty tunnel' values are the mean of six measurements (two positions at each of three speeds). The curves show a consistent increase in the jet diameter with increasing blockage, and the mean increase in cross-sectional area, ΔC , has been derived arithmetically from the data presented in Fig 5a for each plate size. The measurements are mean readings of unsteady pressures, with variations which are considerable compared with the small differences of interest, and it is arguable whether it is better, from the point of view of final accuracy, to use the 'empty tunnel' results taken as the average of only two measurements as a datum at each speed, or to use the average of the six measurements at the three speeds - as a single datum for every speed. The values of $\Delta C/C$ derived using both of the above definitions of the datum are plotted in Fig 5b. The measured increase in wind-stream cross-section, about 1.5S, is much less than the bubble cross-section, about 3.2S as indicated in Ref 2. A considerable difference in this sense can be expected as the low static pressure in the bubble, about -0.35q, is associated with increased velocities in the airstream adjacent to the outside of the bubble.

3 CONCLUSIONS

The variation with blockage of flat-plate base-pressure in closed wind tunnels is in fair agreement with Maskell's theory[1], which predicts a correction linearly dependent on $C_D S/C$. The measurements suggest rather less variation with blockage, at values of $C_D S/C < 0.01$, than the theory predicts, but this discrepancy is not considered sufficient to be of practical significance in using the theory to correct measured data for blockage effects. For values of $C_D S/C < 0.03$ a fair approximation to the blockage correction in an open tunnel is $-0.2 \times$ (closed tunnel correction), though, with larger blockage, a variation more nearly dependent on $(C_D S/C)^2$ appears more appropriate.

Appendix

FACTORS AFFECTING BASE-PRESSURE MEASUREMENTS

It was noted during the tests described in this Report that the base-pressure measured on flat plates normal to the airstream could be affected by three factors in particular - support interference, Reynolds number and vibration - as well as tunnel blockage.

A.1 Support interference

Measurements of drag (section 2.1) were made using three support systems behind the plates - a capacitor drag balance, an existing strain-gauge balance rig and an improved version of the strain-gauge balance rig with the main support moved further back from the plates. Measurements of base-pressure were also made using the same three support systems, and these results are compared in Fig 6 with measurements made using a long 12.7mm diameter spindle as a support, as shown in Fig 1. The cross-sectional distributions of these four support systems are shown in Fig 7 with an indication of the bubble size for three plates, scaled from Fig 1 of Ref 2. In practice, due to tunnel blockage, the bubble size would be expected to be greater, in an open tunnel, than is indicated for the larger plates, and it was confirmed by surface-tuft observations that the downstream end of the bubble behind the 336mm square plate was slightly downstream of the supporting strut of the spindle rig, instead of upstream as shown.

If the measurements with the two strain-gauge rigs are compared with those with the spindle rig, a clear trend is apparent. If the rear of the bubble closes on the roughly parallel part of the supporting system there is a positive pressure error, but when the rear of the bubble is intersected by the supporting strut a negative pressure error results. The former was confirmed and examined quantitatively by making measurements with various spindle sizes as discussed in section 2.2. It was inferred that due to the effect of the supporting strut, the measured base-pressure for the 336mm square plate in the open tunnel was probably too low, by about 0.02q and the value plotted in Fig 4 includes this correction. In the closed tunnels the bubble would be smaller and no error in the base-pressure measurements is expected from the presence of the strut. The addition of the capacitor balance to the 12.7mm diameter spindle rig has only a small effect and it is not clear whether the differences shown are significant when compared with the apparent accuracy of measurement of about 0.005q.

A.2 Reynolds number

151 Due to tunnel-speed limitations, it was not possible to make base-pressure measurements on the 57mm square plate at the same Reynolds number as was used for

the other sizes of plate (Table 1). Measurements over a range of wind-speed on the 57mm square plate suggest that, to allow for the tests being made at about 0.65 of the standard Reynolds number, a correction of +0.005q should be made to the base-pressures measured on this plate, to make them consistent with the measurements on the other plates. This small correction has been applied to the base-pressures measured on the 57mm square plate before plotting the values shown in Fig 4.

A.3 Vibration

The flow behind a bluff base is unsteady leading to fluctuations in pressure over the base surface and vibration of the body producing the separated flow region, unless ocnsiderable care is taken with the mounting system. During the base-pressure measurements on plates normal to the airstream reported in this note several instances of vibration occurred and the following points were noted.

(a) In one case a severe lateral oscillation was set up amounting to about ±5 mm with the 180mm square plate. The base-pressure when the plate was oscillating was changed by about −0.1q compared with the measurement with the plate stationary.

(b) Noticeable lateral vibration of the order of ±1.5 mm could produce an error in the same sense of up to 0.01q, but slight vibration of perhaps ±0.2 mm did not have a measurable effect.

(c) Longitudinal vibration of about ±0.5 mm did not have any measurable effect.

All results quoted are for measurements with barely visible vibration, additional bracing to the supporting strut being required to achieve this in one tunnel.

Table 1

DETAILS OF PLATES AND TEST CONDITIONS

Length of plate side, ℓ (mm)		57	127	180	220	284	336
Area of plate, S (m^2)		0.0032	0.016	0.032	0.048	0.081	0.113
Thickness of plate, t (mm)		2.0	3.3	3.3	5.8	7.8	9.1
Thickness ratio, t/ℓ		0.035	0.026	0.018	0.026	0.027	0.027
Test speed (m/s)		61.0*	42.7	30.5	24.4	18.3	18.3
Reynolds number $\times 10^{-6}$ based on ℓ		0.24*	0.37	0.38	0.37	0.36	0.42
Radial positions of rear-face pressure tappings, fraction of $\ell/2$					0.32	0.33	0.33
		0.50	0.60	0.50	0.60	0.60	0.60
			0.79		0.80	0.81	0.81
Tests made with spindles of diameter, d (mm)	6.35	✓					
	12.7	✓	✓	✓	✓	✓	✓
	19.05		✓	✓			
	25.4		✓		✓		
	31.75		✓			✓	
	36.3						✓

* In the No.1 11½ft × 8½ft tunnel tests were made at the maximum tunnel speed of 54.9 m/s, RN = 0.22×10^6.

LIST OF SYMBOLS

C	empty tunnel cross-sectional area (m^2)
ΔC	increase in airstream cross-section due to blockage in an open tunnel (m^2)
d	diameter of spindle used to support the plates, Fig 1 (mm)
C_D	drag coefficient in terms of q
C_{D_C}	drag coefficient corrected to zero blockage, *ie* in terms of q_c
ℓ	length of one side of a square plate (mm)
C_{p_b}	plate base pressure in terms of q, corrected to zero spindle diameter
C_{p_c}	plate base pressure corrected to zero blockage (*ie* in terms of q_c), corrected to zero spindle diameter
C_{p_m}	measured plate base pressure in terms of q, with mounting spindle present
q	empty tunnel dynamic head ($N\ m^{-2}$)
q_c	effective tunnel dynamic head in the presence of blockage ($N\ m^{-2}$)
r	radial position in open tunnel (m)
R	nominal radius of airstream in open tunnel (m)
S	plate area (m^2)
t	plate thickness (mm)

REFERENCES

No.	Author	Title, etc
1	E.C. Maskell	A theory of the blockage effects on bluff bodies and stalled wings in a closed wind tunnel. RAE Report Aero 2685 (R & M No.3400) (1963)
2	R. Fail J.A. Lawford R.C.W. Eyre	Low-speed experiments on the wake characteristics of flat plates normal to an airstream. RAE Report Aero 2516 (R & M No.3120, 1959) (ARC 19958) (1957)

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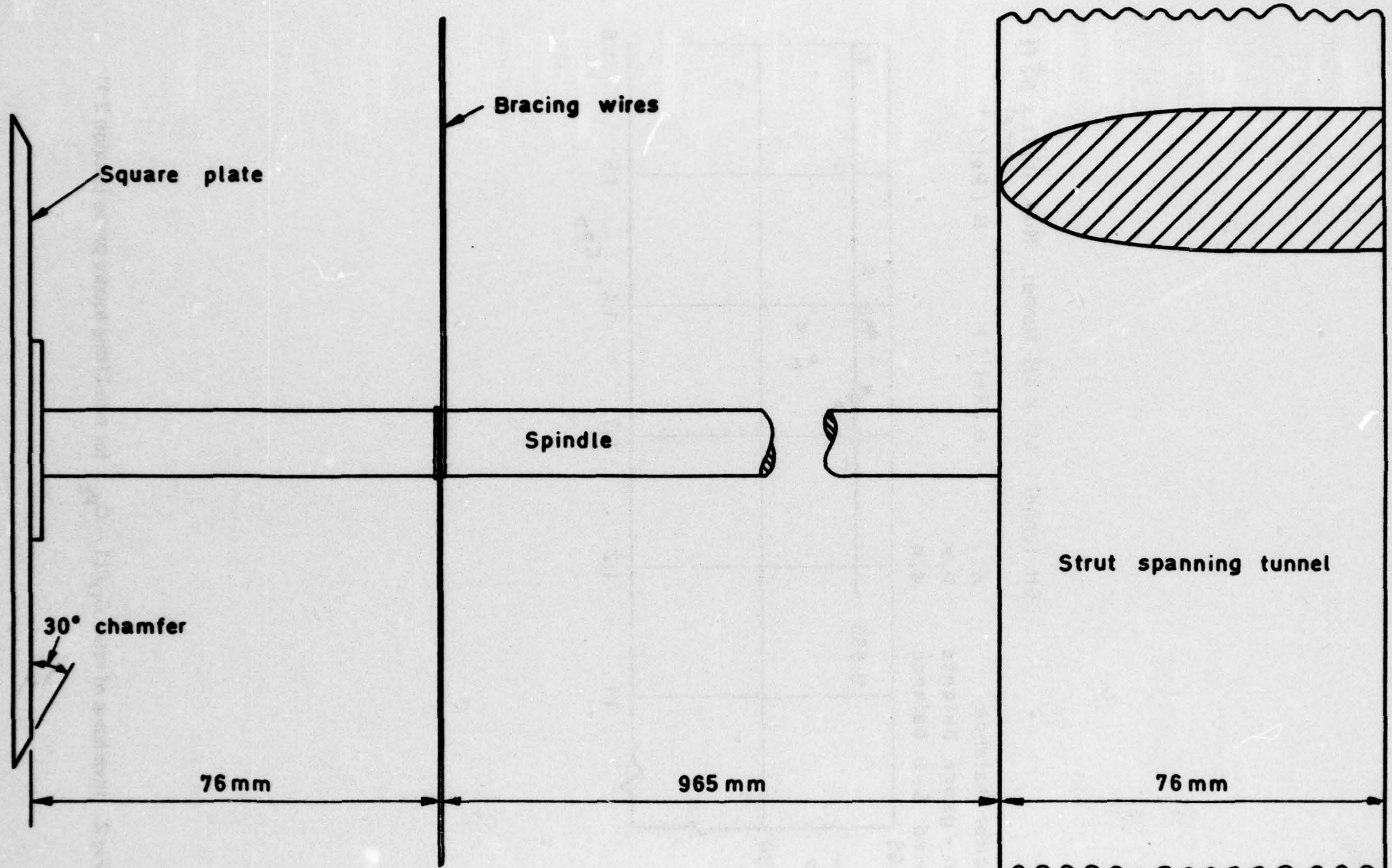

Fig 1 Rig for mounting plates normal to the airstream

Fig 2

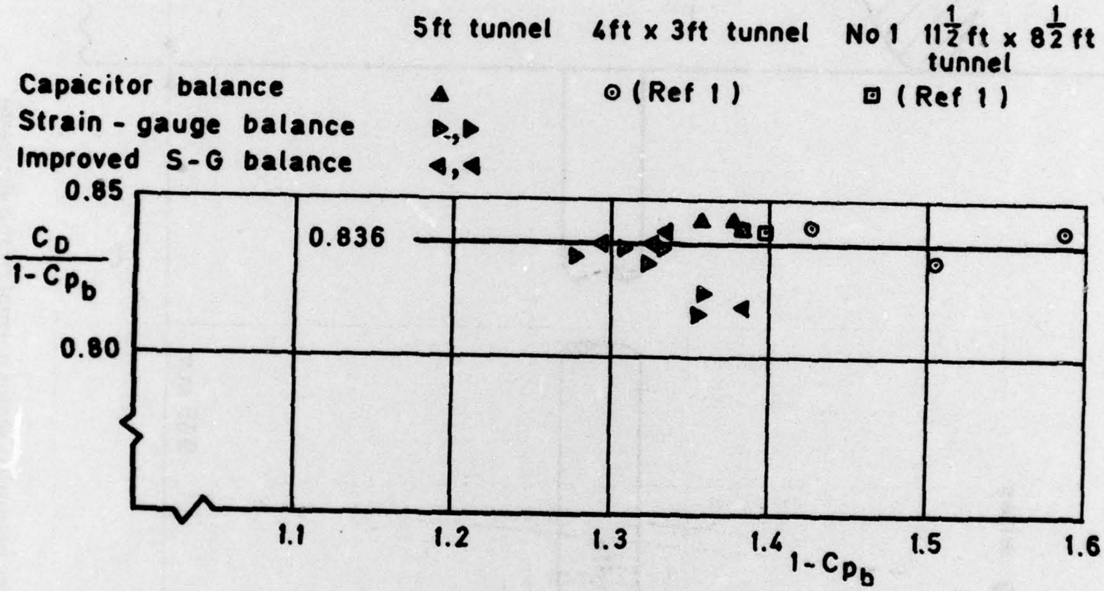

Fig 2 Invariance of ratio $C_D/(1-C_{p_b})$ for non-lifting square plates (section 2.1)

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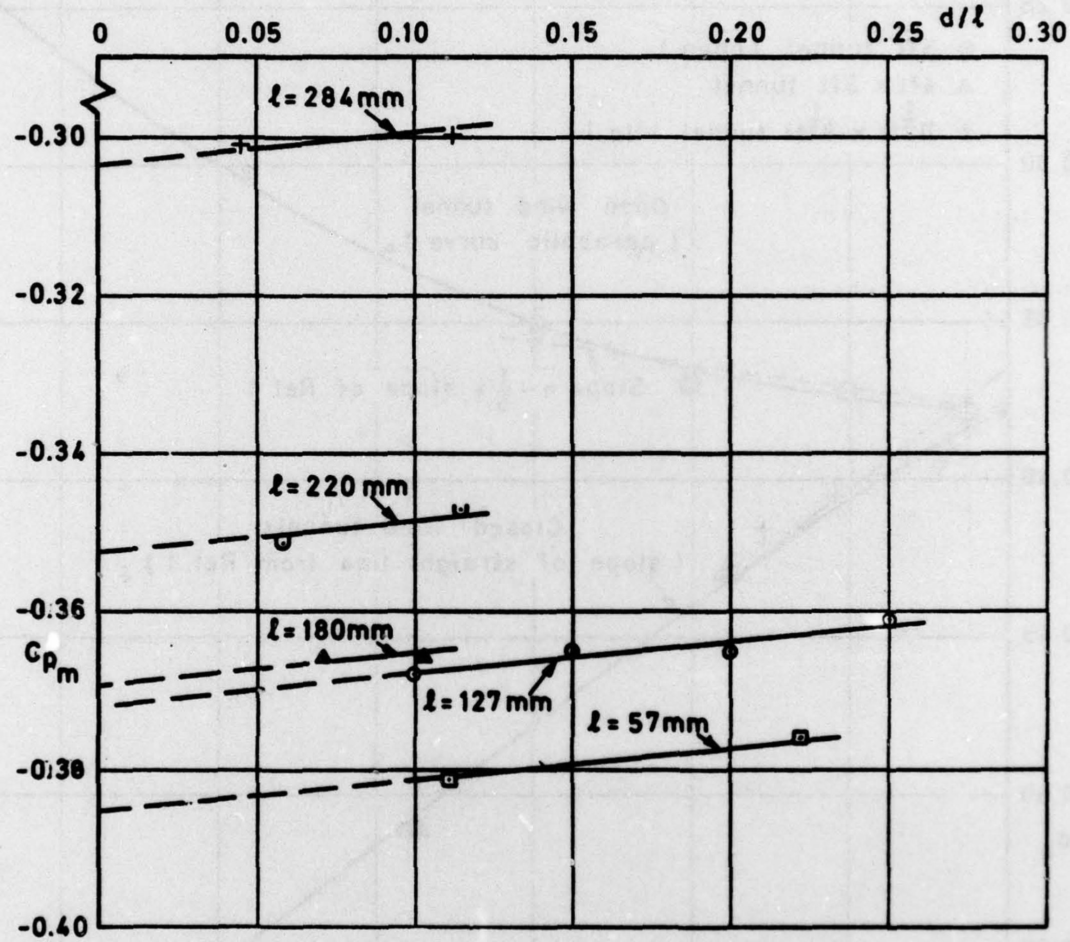

Fig 3 Effect of spindle size on plate base pressure in 1.52m diameter open tunnel. Lines are drawn at constant slope = 0.04

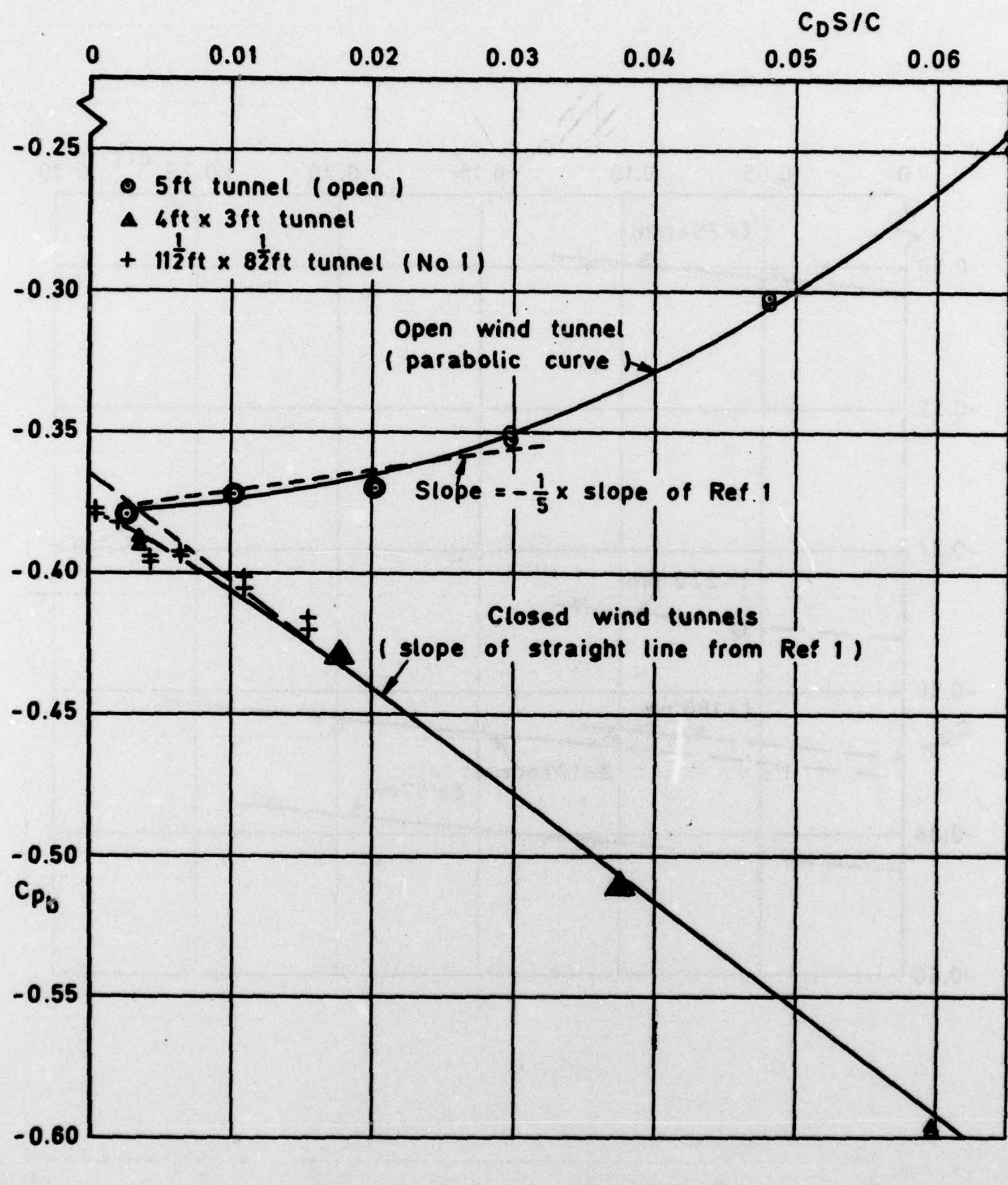

Fig 4 Blockage effect on base pressure. Non-lifting square plates

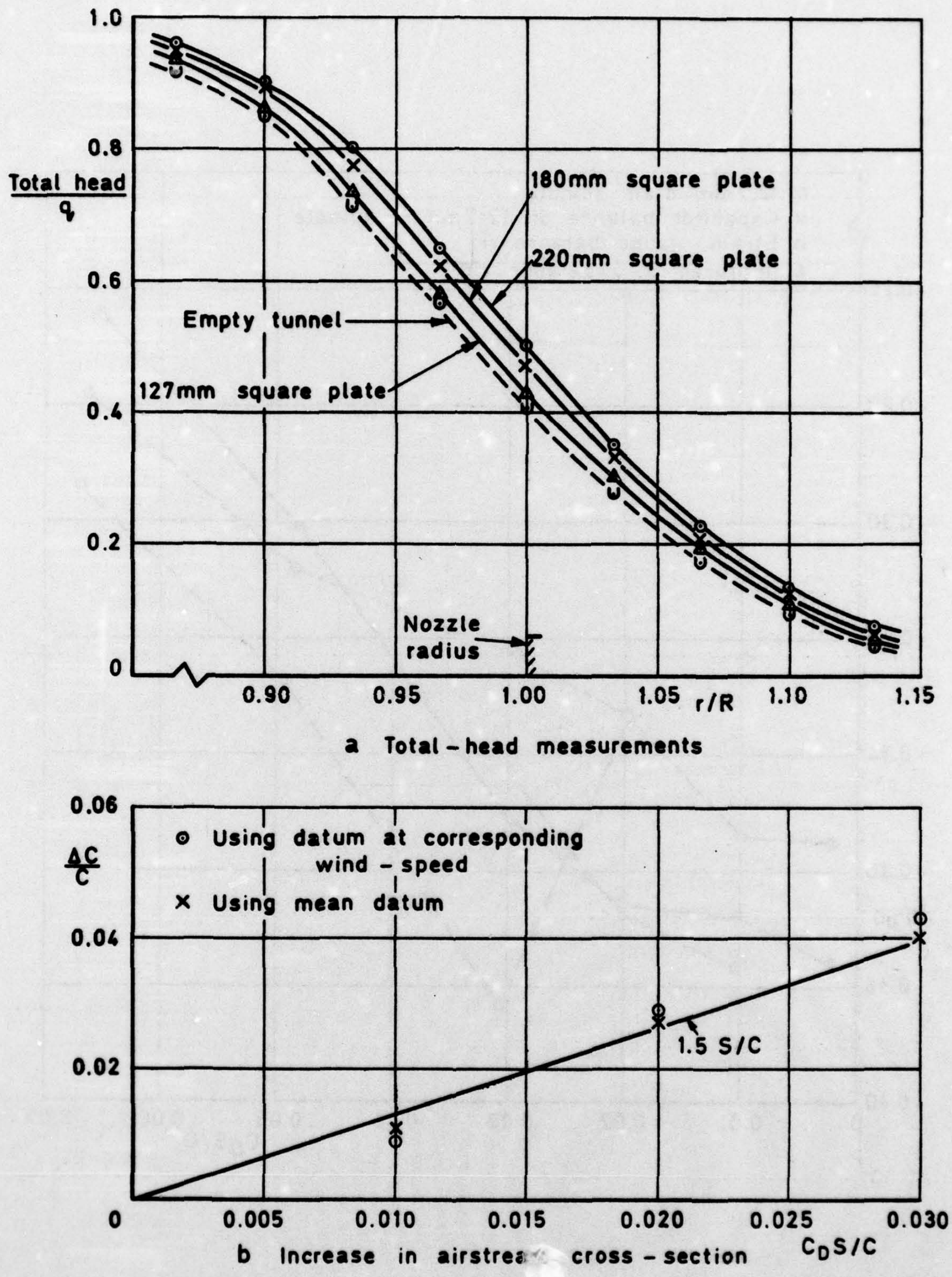

Fig 5a&b Effect of blockage on open tunnel airstream cross-section. Nominal 1.52m diameter airstream. Measurements in plane 1.24 m from nozzle, 0.25 m downstream of plates

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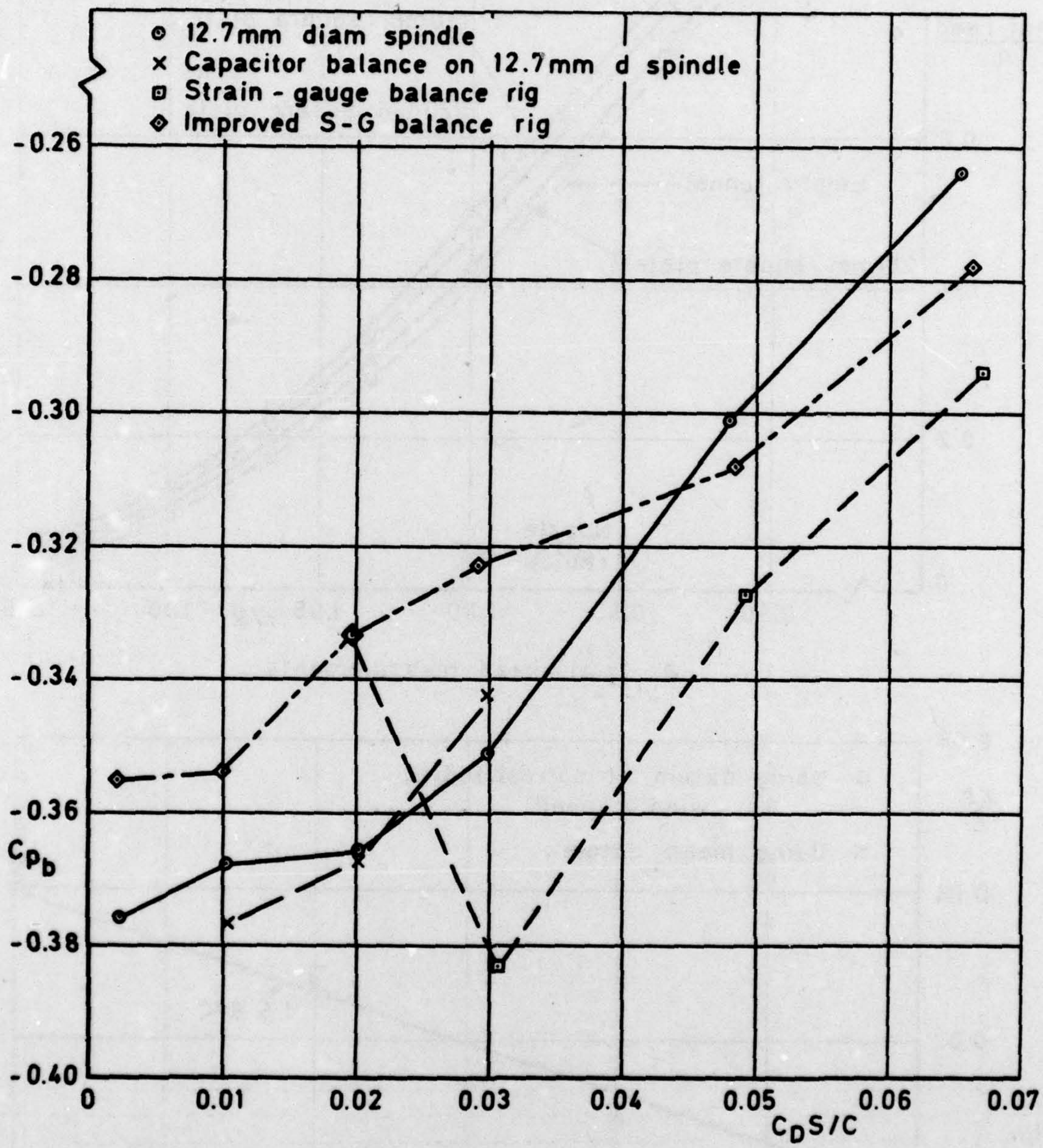

Fig 6 Effect of rig interference on measured base pressure. 1.52m diameter open tunnel. Rig configurations shown in Fig 7

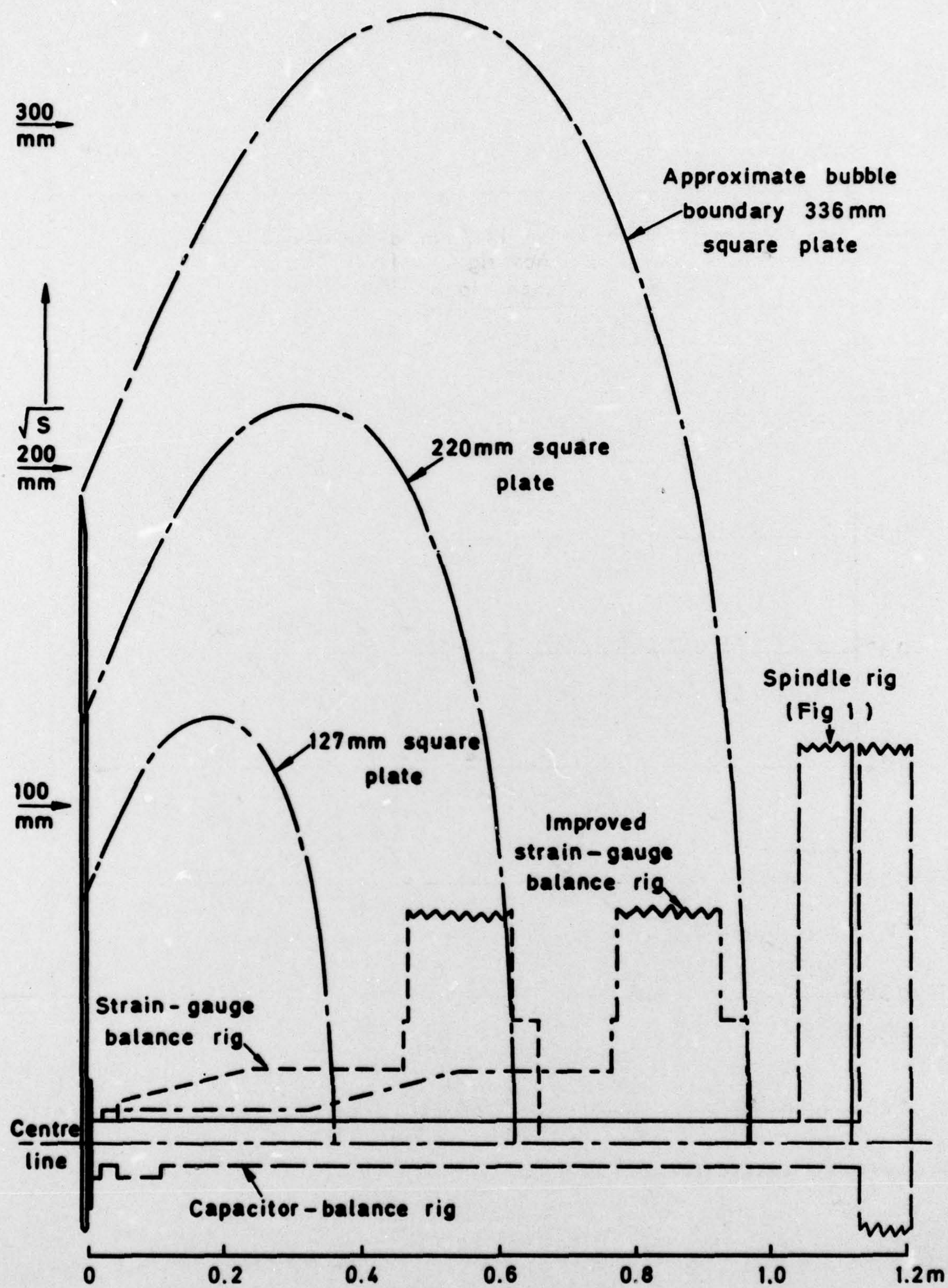

Fig 7 Cross-sectional areas of rigs used to mount the plates in the 1.52m diameter open-jet tunnel

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17\. Abstract

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